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TESTS WITH A LINE-COMMUTATED CONVERTER AS A VARIABLE INDUCTIVE LOAD ON THE
BONNEVILLE POWER ADMINISTRATION TRANSMISSION SYSTEM*

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Abstract — A twelve-pulse, line-commutated converter, with a steady-state rating of 2.5 kV and 5.5 kA, formerly used for charging and discharging a superconducting magnet, was reconfigured as a static reactive power load. Tests staged at the Tacoma, WA, substation of the Bonneville Power Administration (BPA) revealed that the converter could be used as a variable inductive load, provided a stable current controller was installed. The unit was modulated as a variable VAR load following a sinusoidal VAR demand signal with an amplitude up to 14.8 MVAR. The total losses at maximum VAR output were 370 kW.

This paper explains the necessary modifications of the converter to operate as a variable reactive load. Measured current waveshapes are analyzed. The effects of such a load on the BPA transmission system are presented.

1. Introduction

A 30 MJ superconducting magnetic energy storage (SMES) unit was operated at the BPA substation at Tacoma, WA, from February 1983 to February 1984. This was a joint project between BPA and Los Alamos National Laboratory. Upon completion of the project the authors suggested that the SMES conversion equipment be used as a variable inductive load, which, combined with a fixed-value, parallel-connected capacitor, would constitute a static VAR device. Because the SMES conversion equipment was not designed for this alternate mode of operation, it was felt appropriate to conduct some variable reactive power tests with the equipment at Tacoma. In the previous years real power sinusoidal modulation tests with values up to ±8.6 MW had been staged with the equipment, using a superconducting coil as a load [1,2]. However, because of the absence of the superconducting coil, which had imposed a current limit on the system, and the known conservative converter design, it was assumed that a higher current loading of the converter could be accomplished in inductive load tests.

2. SUMMARY OF CONVERTER DESIGN

The SMES converter is a twelve-pulse, line-commutated, air cooled unit, which consists of two six-pulse bridges connected in series[3]. Each bridge has a rating of 1.25 kV, 5.5 kA, resulting in the converter rating of 2.5 kV, 5.5 kA. The negative converter voltage is limited to 2 kV because of the inversion end stop to guarantee safe current commutation. The converter is connected to the 13.8 kV bus by two 6.0/7.5 MVA, OA/FA, transformers, which have a voltage ratio of 13.8/0.928 and a short circuit impedance of 8.8%. Each bridge leg consists of eight SCRs in parallel. The SCRs are 50 mm devices with a repetitive blocking voltage of 3200 V and an average forward current of 800A. Each

bridge has a set of eight bypass SCRs, which are rated to conduct the steady-state load current.

3. REACTIVE POWER OPERATION OF CONVERTER

It is textbook knowledge[4] that by delaying the phase angle α in a line-commutated converter for constant apparent power, the relationship between real and reactive power can be changed. If an ideal converter is assumed with no commutating reactances, then no reactive power is absorbed for a zero phase delay angle. At $\alpha = 90°$ only reactive power is taken from the feeding ac system. This relationship for an ideal converter is shown in Fig. 1. To run the SMES converter as a variable inductive load, the phase delay angle must be adjusted to vary near $\alpha = 90°$. Changes in reactive power are made by momentarily changing the phase delay angle. A phase delay angle of less than 90° will increase the load current and therefore the reactive power. A phase delay angle of higher than 90° will decrease the load current and reactive power.
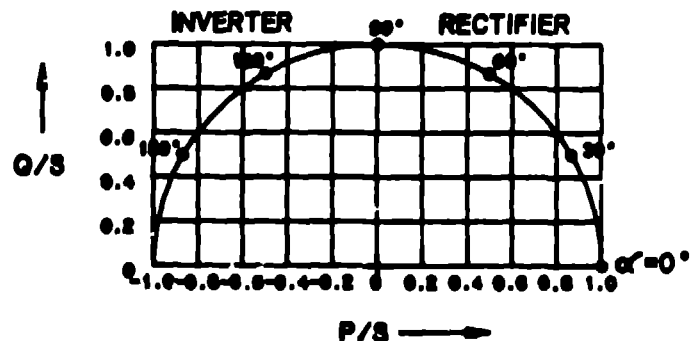
Fig. 1. Relationship between real power (P) and reactive power (Q) for constant apparent power (S) of an ideal line-commutated converter with the phase delay angle α variable.

An ideal shorted converter, operating at $\alpha = 90°$, absorbs only reactive power. Figure 2 shows that for a six-pulse bridge the line current is limited only by the commutating impedance and can have excessive values for small impedances. The line current is continuous for phase delay angles of 90° and smaller. If the phase angle is delayed more than 90°, as shown in Fig. 2e, the line current becomes discontinuous. In a six-pulse bridge with the discontinuous current mode there are six load current pulses per cycle. Figure 3 shows the shape of the line current of the one bridge of the SMES converter which is connected to the wye-delta transformer. The current shape in Fig. 3 agrees with the one shown if Fig. 2f, if the transformer connection is taken into account. The discontinuous current has a high harmonic content which is undesirable in a power system. To improve the line current wave shape of the SMES converter, a small inductance was added in the load circuit to provide more continuous load currents. The

load inductance consisted of three 2000 A carrier current line traps connected in parallel. Each coil had an inductance of 228 μH and a resistance of 850 μΩ, resulting in a total load of 76 μH and 283 μΩ.
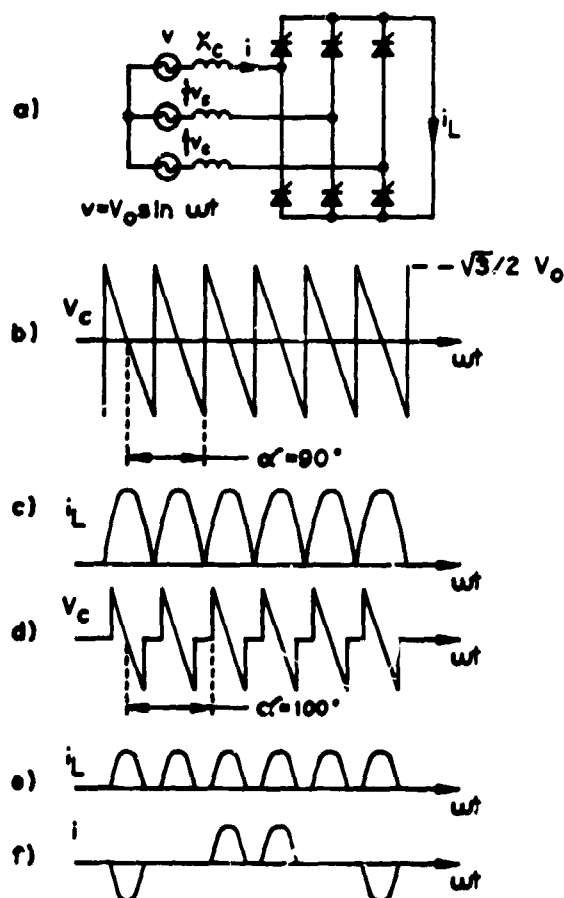
Fig. 2. Six-pulse, short-circuited bridge
   a) circuit diagram,
   b) voltage across two commutating inductances v_c for $\alpha = 90^\circ$,
   c) load current i_L for $\alpha = 90^\circ$,
   d) voltage across two commutating inductances v_c for $\alpha = 100^\circ$,
   e) load current i_L for $\alpha = 100^\circ$,
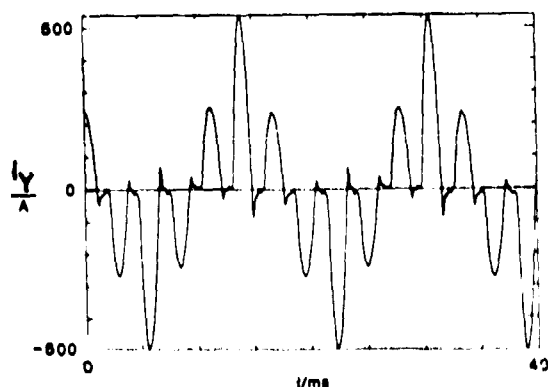   f) line current i for $\alpha = 100^\circ$.

Fig. 3. Line current (at 13.8 kV) of a wye-delta transformer connected to a six-pulse, short-circuited converter.

4. DEVICE RELATED TEST RESULTS

The electrical circuit for the inductive load test is shown in Fig. 4. It should be pointed out that the average converter output voltage should be kept below 2 V for a rated load current. This is 0.08% of the

available converter output voltage of 2500 V. Because of the high ripple content of the output voltage controlled at $\alpha = 90^\circ$, a voltage controller is not suitable to provide stable, closed-loop control. A fast acting current controller, in which the demand current is compared with the actual load current, provided stable operation of the unit, even at very small current levels (350 A). The delay between the load current demand signal and the actual current was measured to be 6 degrees for a 0.65 Hz signal.
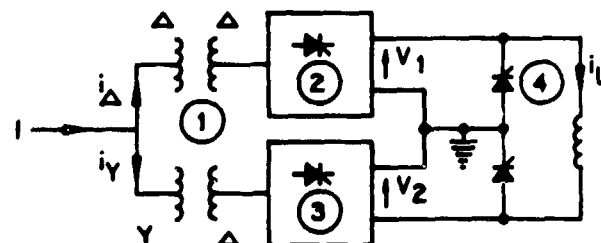
1. CONVERTER TRANSFORMERS, 6MVA EACH
2. 6-PULSE BRIDGE (1.25 kV, 5.5 kA)
3. 6-PULSE BRIDGE (1.25 kV, 5.5 kA)
4. BYPASS SCRS
5. INDUCTANCE (76 uH, 283 uΩ)

Fig. 4. Circuit diagram of twelve-pulse converter for inductive load tests.

The current controller also keeps the current limited during the initial turn-on. To be conducting, the SCRs of the converter must be supplied with a voltage greater than the forward breakover voltage, which is gate current dependent and several times higher than the rated load voltage. During start-up the current controller limits the current overshoot to a minimum.

Because of the existence of the bypass thyristors, each bridge could be tested individually. Figure 5 shows the line currents at different loading for both bridges. The waveshape of Fig. 5b should be compared with Fig. 3 to see the smoothing effect of the load impedance on the harmonic content of the line current. For currents less than those shown in the top traces of Fig. 5, the line current and load current is discontinuous. The line current can be continuously controlled from zero to a maximum value. Therefore, in a six-pulse circuit, the reactive power can vary from zero to the maximum value. If the converter is operated as a twelve-pulse converter, a discontinuous current operation is impossible, which limits the reactive power to a minimum value. Discontinuous current flow is not possible because two SCRs in each bridge must always be conducting. This condition is met only when the instantaneous output voltage of each bridge is positive initially. This occurs for a phase delay angle of less than 90°.

The SMES converter could produce a minimum load of 350 A, below which value the load current would cease to flow. The converter was tested for average load currents between 350 A and 6000 A. The upper value exceeded the design rating by 10%. The line current wave shapes for twelve-pulse operation with the load current increasing are shown in Fig. 6. A reconstruction of the line current shape starting with the converter output voltage and current is shown in Fig. 7. In the example the lower current limit has been chosen (compare with Fig. 6a).

5. EFFECTS OF Q MODULATION TESTS ON AC SYSTEM

Besides the steady state tests, load modulation tests were performed at frequencies between 0.1 and 0.75 Hz. The dominant resonance frequencies of the Pacific AC Intertie lie within this frequency band. Figure 8 shows as an example modulation tests at 0.1 Hz.
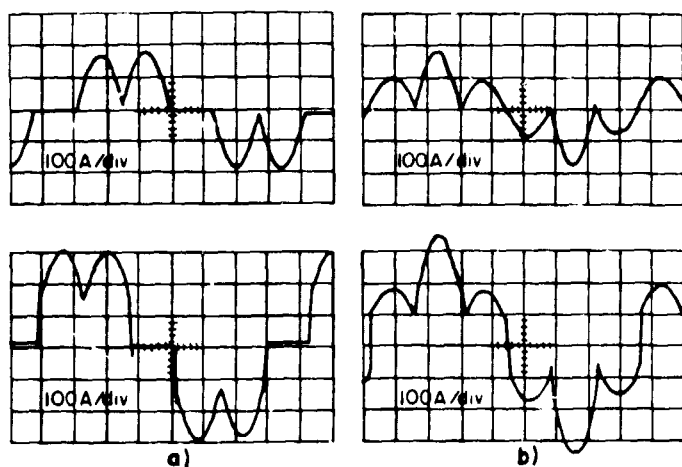
Fig. 5. Line current (at 13.8 kV) of six-pulse bridge under different loading conditions with converter transformer connected in, a) delta-delta configuration, b) wye-delta configuration. The top traces show light loading of the converter (average load current 2000 A), the bottom traces heavier loading (average load current 3800 A); scale 2 ms/div.
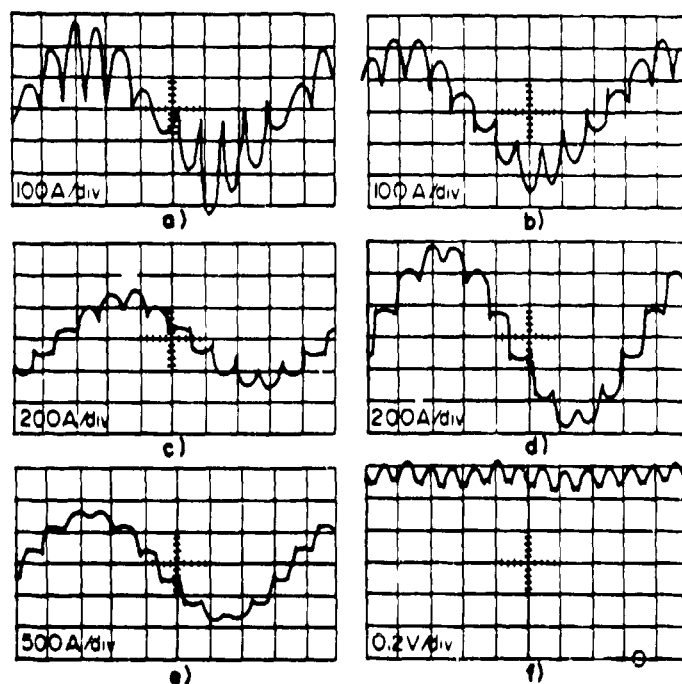

Fig. 6. Current wave shapes of modulated, twelve-pulse bridge, operating into a low inductive load; line current (at 13.8 kV) with increasing average load current I_L, a) 700 A, b) 1400 A, c) 2100 A, d) 4000 A, e) 6000 A, f) load current i_L at average load current I_L = 5.5 kA; scale 2 ms/div.

The average load current varies between 360 A and 6000 A. The average load current, the real power consumption and the reactive power absorption are shown. At 6 kA the absorbed reactive power is 14.8 MVAR and the total (transformer, converter, load, fan) losses are 370 kW.

The complex-power load, which the converter presented to the ac system while being modulated at 0.15 Hz, is shown in Fig. 9. The test oscillator
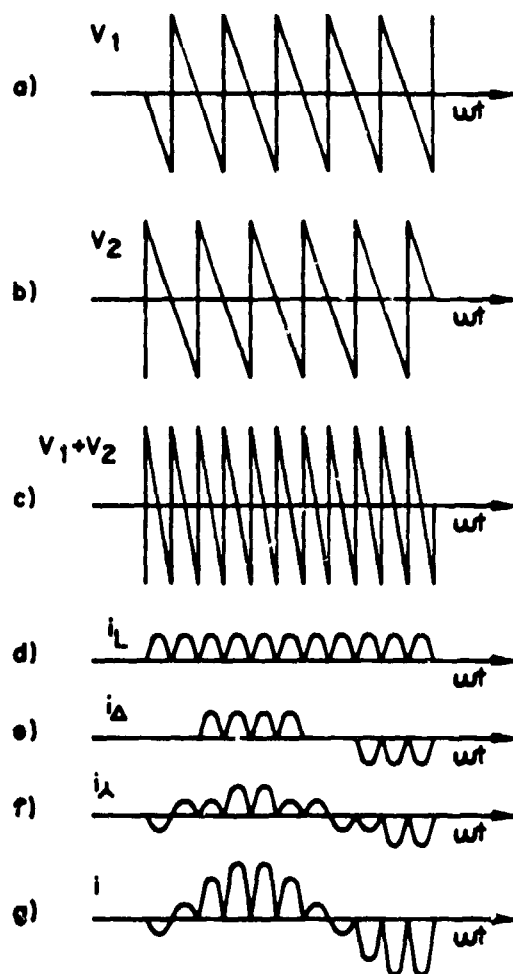

Fig. 7. Twelve-pulse bridge operating at $a=90°$ into a low impedance load
a) converter voltage V_1,
b) converter voltage V_2,
c) total converter output voltage $V_1 + V_2$,
d) load current i_L,
e) line current i_Δ,
f) line current i_Y,
g) line current, i.
(see Fig. 4 for definitions)

provided the modulation signal Q_{mod} at very low distortion. The real and reactive power response (P and Q) exhibit harmonics which are roughly 60 db below the fundamental. The real power P is 35 db below the reactive power Q.

Figure 10 shows the response of the Pacific AC Intertie power to the reactive power modulation at 0.30 Hz. The peak as shown in the autospectra at 0.30 Hz stems from the modulation signal. This result also can be confirmed by the coherency function, which is not shown. The peak is lacking in Fig. 11, which depicts modulation response at higher frequencies. Response is very small for frequencies above 0.35 Hz. The rather variable peaking near 0.22 Hz is unrelated to the modulation input and is characteristic of ambient activity observed on the AC Intertie. Test data of Figs. 9-11 are given in relative amplitudes and contain conversion factors of the instrumentation and metering devices.

Intertie response was checked at 6 frequencies between 0.1 Hz and 0.75 Hz, and was found to be highest at 0.30 Hz with a value of 0.42 MW/MVAR. Response near 0.7 Hz was approximately 30 db lower than that near 0.3
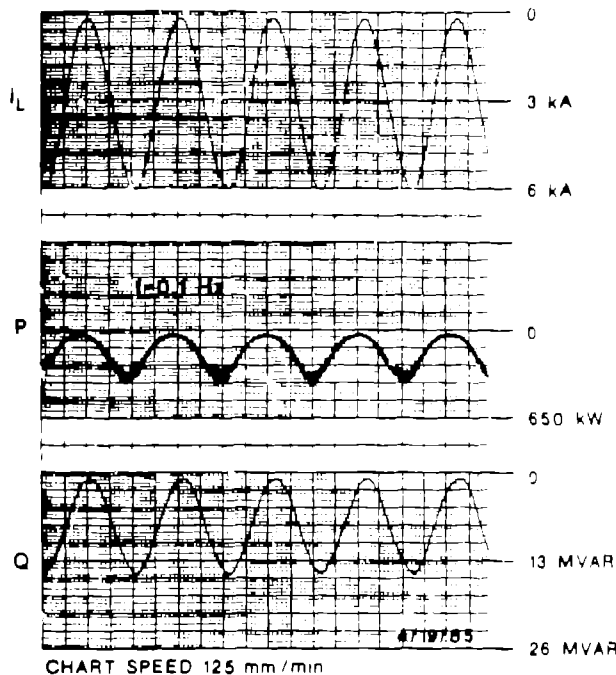
Fig. 8. Output parameters of a modulated twelve-pulse converter, operating at $\alpha=90^\circ$ into a low impedance inductive load,
a) load current i_L,
b) real power P,
c) reactive power Q,
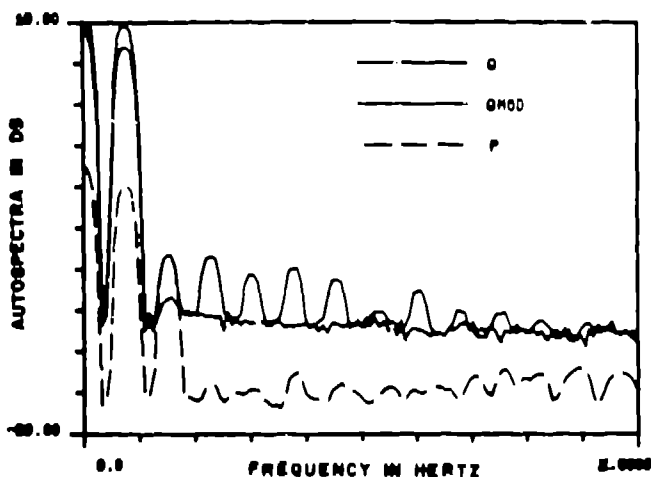(note: center trace is advanced by two divisions)

Fig. 9. Autospectra for response of converter demand to sinusoidal modulation at 0.15 Hz.

of the peaking that was predicted by some BPA swing studies[2]. Response to the Q modulation on the feeding 13.8 kV bus was about 4% rms at all test frequencies.

SUMMARY

An existing twelve-pulse, line-commutated converter was modified to operate as a variable inductive load up to a level of 14.8 MVAR. A stable current controller allowed the unit to operate without exceeding rated currents, although the average operating voltage was necessarily restricted to less than 0.1% of the maximum available voltage. Reactive power modulation tests revealed that the unit produced low level but distinct response on the Pacific AC Intertie.
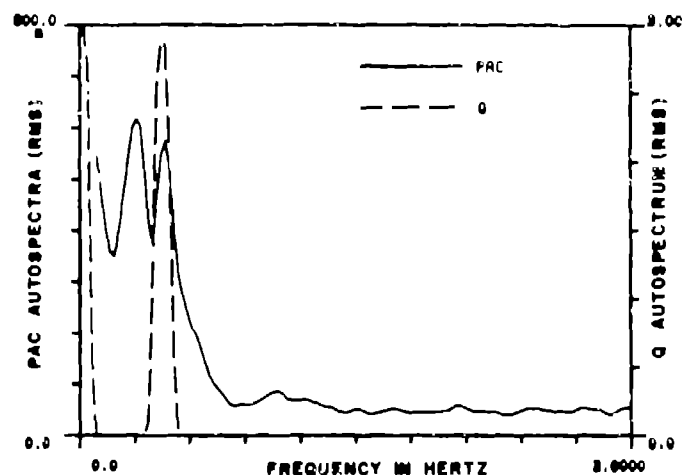

Fig. 10. Autospectra of AC Intertie power and converter reactive power for sinusoidal modulation at 0.30 Hz; 1039-1047 hrs; 4/19/85.
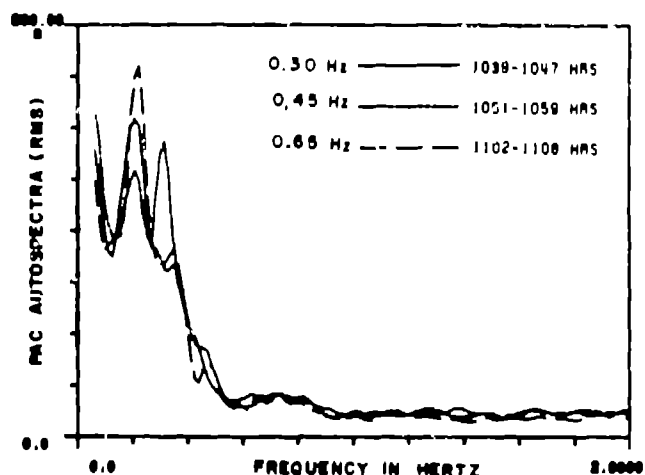

Fig. 11. Autospectra of AC Intertie power for sinusoidal modulation at 0.30, 0.45, and 0.65 Hz; 4/19/85.

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